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THE FUTURE DIRECTION AND DEVELOPMENT OF ENGINE HEALTH MONITORING (EHM) WITHIN THE UNITED STATES AIRFORCE

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ABSTRACT

1. The ability to trend an engine's health & performance has been possible ever since Hero of Alexandria fired-up his steam driven Aerolipile in around 100BC. However, the development of any engine health monitoring (EHM) system has historically been driven by a need to resolve an operational dilemma. Unfortunately the goal of EHM technologies has sometimes never been clear or achievable because the described problem and need have not been fully understood; so the realization of the ability to monitor and predict an engine's life, health and performance has never kept abreast with the technology it is trying to support.

2. The DOD's is developing engines towards increased power to weight goals with a need to show reduced life cycle costs and improved reliability; obligating major advances in control, diagnostic and prognostic technologies. The acquisition of real-time engine data is already achievable, however the interpretation and utilization of such data is still difficult, even after 2000 years. Current activities that are being investigated for the development of EHM technologies will demonstrate a cognitive (acquire knowledge) ontogenetic (learning) monitoring ability that can accurately predict a gas turbine engine's health (the overall soundness) performance variation (degradation), component life (e.g. LCF, HCF and Creep) consumption based on real or virtually sensed engine data. Therefore the development of an aware, learning and reasoning EHM system is the missing link between our current diagnostic confused situation, and a status of having a true diagnostic with prognostic (knowledge with wisdom) capability.

3. The USAF's research & development activities are firmly assisting in the evolutionary work that is required to provide a future EHM system that is artificial intelligence (AI) based. This paper will detail the EHM activities that are currently being investigated to achieve the process of turning data into information into knowledge and finally into wisdom. Moreover it will focus on describing the approach and bias that must be taken on the development of a gas turbine EHM system for health and life management. It will define how data integrity, compression and fusion will feature as the first link towards achieving a truly cognitive ontogenetic (CO) (aware and learning) EHM system. Additionally by developing and applying reasoning science, like that provided by a probabilistic diagnostic and prognostic system (ProDaPs), we can then achieve an assemblage that could be described as truly artificially intelligent; namely in structure, judicious reasoning and execution. These activities will bring about philosophies, methodologies and technologies to make accurate predictions and provide technical solutions to reduce an engine's life cycle cost, enhance flight safety and strengthen operational capability.

THE ENGINE MONITORING (EM) GOALS

4. The increasing emphasis on improved affordability, availability and safety prompted has prompted an investment in improved embedded engine diagnostic technologies; this approach has been called 'Autonomics'. The focus of this investment was to select the "low hanging fruit," i.e. the relatively high value low risk problems. Although extensive improvements in diagnostic capability for controls, accessories and lubrication system components have been incorporated in the latest generation engines, the diagnostic coverage for gas path does requires further development. Problems with gas path structures relate to approximately 30% of current fighter engine in-flight shutdowns.

5. The DOD's/USAF's Integrated High Performance Turbine Engine Technology (IHPTET) goals for performance, weight reduction, reliability and life cycle costs will need accurate and timely data. These objectives will only be achieved through an EM system that provides real time monitoring and health information. Therefore IHPTET needs a COEHM system that will monitor, trend, diagnose, predict and inform. This paper addresses some of the research and development programs and the required methodologies that will help achieve real time AI EM. The goal is to have the right action at the right time for the right reason. i.e. the 3 Rs of EHM.

EM DEVELOPMENT

6. The development of an AI EM system will need to use tools such as data filters, polynomials, fuzzy logic, expert systems, probabilistics and neural networks. This list is not exhaustive and will require the application of novel approaches to give the system the ability to make accurate prediction before the event it is monitoring happens. A COEHM system will provide fast and accurate diagnostic and prognostic information to reduce maintenance times, no fault founds and turn round times. The improved critical life management aspect will reduce engine life cycle costs. Therefore the development of a COEHM system will considerably reduce engine cost of ownership, enhance operational capabilities and overcome loss of technical experience due to personnel downsizing.

COEHM METHODOLOGY

7. The COEHM Methodology approach (pictorially shown at fig 1) requires an integrity

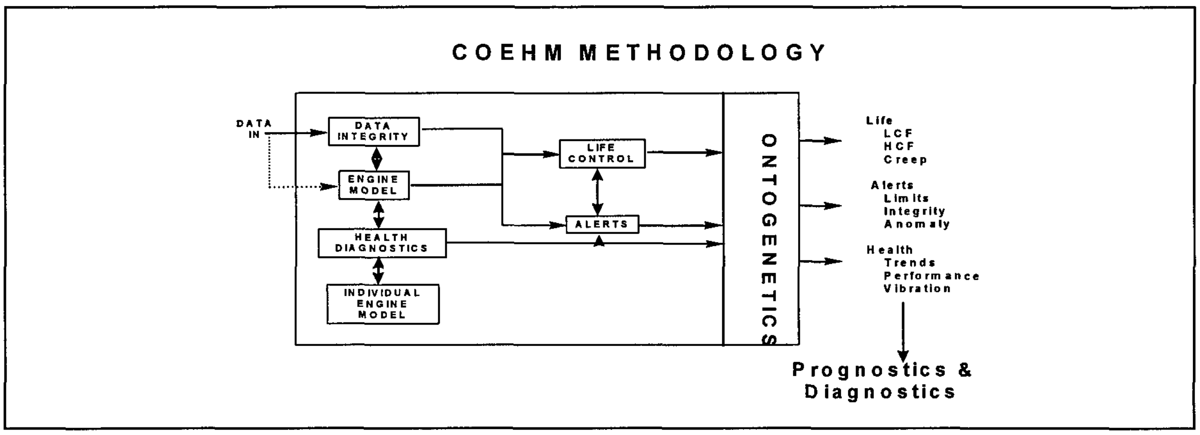

Fig 1

check through a Data Integrity Module for all data inputted and will compare this to empirical data as well as real time model data from the Engine Model Module. The Engine Model Module feeds accurate data for real and derived parameters into the Life Control, Alerts and Diagnostic Modules. The Health Module will be able to make comparisons between the data coming from the engine, those derived from the model and those

performance curves that were obtained during engine pass off and are now contained within the Individual Engine Model Module. The system feeds life, alerts and health data directly to maintenance staff or can be feed through an Ontogenetic Prognostic (i.e. true AI) Module that will improve the probability of identifying the outcome of current or future events; this final module will give the maintainer a true diagnostic and prognostic capability that is accurate and fast. As a modular approach the system concept can be modified to meet the needs of the user and as such can be applied to aging aircraft as well as those currently in service and planned for the third millennium.

8. **COEHM Model Based Diagnostic & Performance Algorithms**. The Engine Model Module is a model based diagnostics system, which can be used to improve performance, increase reliability and sortie generation rate, and so reduce maintenance costs. This system features a real-time, nonlinear, physics based, dynamic model of the engine embedded in the engine controller (FADEC) or as part of the EM system. This model is updated in real-time using a tracking filter to match actual engine characteristics. Model computed values can then be passed to the Health & Diagnostic Module. Some gas path structural failures occur with significant precursors identifiable in performance parameters. To date normalizing performance parameters sufficiently to detect and isolate these precursors has been difficult. The advent of adaptive on-board performance simulations has provided normalized gas path performance parameters that are proportional to changes in engine module performance. This methodology utilizes these parameters and a neural network to improve detection accuracy.

9. **COEHM Health & Diagnostics Approach**. Advancing the USAF's capabilities in engine life measurement, diagnostic and prognostics capability of critical engine components is necessary to improve engine availability, minimize performance degradation, and reduce life cycle costs. Engine data currently sensed and recorded for post flight processing can be analyzed in a continuous real-time mode within the Health & Diagnostic Module. Proven AI technologies such as neural networks, fuzzy logic and expert systems present an opportunity to significantly enhance current trending and diagnostic capabilities in a real-time monitoring environment. For fault detection and accommodation, extensive knowledge of how a healthy engine operates under given conditions will be analyzed, and any deviation from this 'normal' pattern of expected parameters will be detected and further analyzed. The same sensed data will be used as inputs to life usage algorithms in the Life Control Module and will determine critical component remaining life based on actual experienced severity.

10. **Probabilistic Method (PM) for Life Management and Diagnostics**. The use of PM for the development of improved design and life sensitivities has been achievable for some years, and we can now more accurately design and life a component. The growth in computing power has freed this statistical tool and allows the application of resolving tools such as Monte Carlo, Second Order, Taylor Expansion, Orthogonal Array etc. The extension of PM for the production of generic High Cycle Fatigue (HCF) codes will require validation and verification (V&V) of the sensitivities that were applied. The function of a PM V&V tool would be ideally suited to run concurrent with the component, so as to assure that the real time experience reflects the one assumed at the design stage.

11. The ability of a PM code to apply sensitivity to data will further increase the chances of identifying the cause of an engine's fault (diagnostics) or deducing the most likely health or performance outcome (prognostics). Probabilistic as a real-time diagnostic, prognostics and life management tool will be an important contributor to producing a COEHM as well as to help meet the IHPTET goal of reducing maintenance costs. The application of a global genetic 'optimization' probabilistic tool will improve the sensitivity for diagnostic and prognostic speed and accuracy. The use of P M for V&V, fault isolation, identification and prediction still needs further development.

12. **Probabilistic Diagnostic and Prognostic System (ProDaPS)**. The development of a probabilistic diagnostic and prognostic system (ProDaPS) capability for turbine engine health is achievable. It will assist in the development required to provide a future predictive methodology that is able to deduce accurately the outcome of an event, so as to reduce engine life cycle costs and enhance operational capabilities. ProDaPS will provide real-time diagnostic and prognostic assessment of creep and fatigue life, component condition

and life consumption, engine performance and engine health. The system will also integrate performance and historical information to produce its own COEHM capability. The system will ultimately have the ability to V&V probabilistic design and life codes and thus confirm that the assumed PM sensitivities are accurate.

DATA NEEDS FOR A COEHM SYSTEM

13. '**Total System' Sensing**. The need for data integrity is a corner stone of an effective COEHM approach, and the ability to model real time data or virtual data1 are major steps towards a true understanding of the engine's health. However there is a need for a more 'total system' approach to sensing data and this is pictorially shown at fig 2. A 'total system' approach to data sensing will require the application of new advances in sensing technology. The concerns about any sensing expansion is weight and reliability and so the approach must be towards

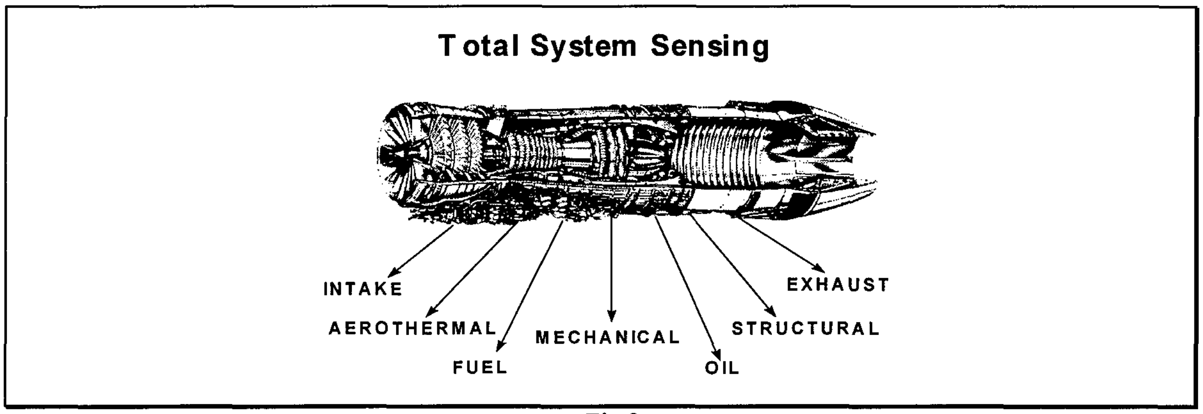

Fig 2

function amalgamation and simplification, e.g. we will develop sensors and methodologies that will perform both vibration and speed or temperature and speed monitoring. The development of more passive sensors will improve reliability in that they only need to detect changes in amplitude or frequency.

14. **FOD Detection & Exhaust Emissions Analysis** . The increasing complexity of modern aircraft inlet structures will increase the maintenance burden for routine inspections for Foreign Object Damage (FOD). FOD detection technology (acoustic, radar or electrostatic) will reduce the maintenance burden by providing an automatic FOD detection capability; it does require detailed signature profiles of events to be effective. The systems are:

a. **Acoustic.** The acoustic approach utilizes close coupled high response pressure transducers and advanced signal processing to detect the acoustic energy emitted when a engine fan blade is impacted by a damaging foreign object. This concept focuses on the characterization of the acoustic signal generated by impact and the detectability of that characteristic within the normal engine background noise environment. Laboratory and engine testing demonstrated that this detection technology is practical with high accuracy for cases of blendable FOD.

b. **Radar**. The radar approach was initially designed to detect blade damage. The system uses a low power radar emission and detection system within the inlet; this approach has already been able to detect 1mm defects in blades as far back as the compressor's third stage. The system goal is to determine the type and characteristics of all possible FOD ingested by an engine. The technology can already derive velocity and relative mass and can determine the difference between a split pin and other metallic objects.

c. **Electostatic**. The electrostatic approach monitors both the inlet and outlet gas path. It employs an electro-magnetic detector in the inlet as well as one in the outlet. The system monitors the change in ionization of the gas path and is more complex than the approaches detailed above and as such requires a

high rate of data acquisition and considerable computer power to perform diagnostic and prognostic evaluations. Electrostatic Engine Monitoring (EEM) has been a technology that has shown promise since the early 1970s. Many evaluations from laboratory, to engine and flight testing have shown that material within the engine gas path is detectable as charge particles either entering or exiting the engine gas stream. The early attempts to employ this technology were troubled by false indications and problems in setting thresholds for normal versus abnormal signatures. New sensing electronics and signal processing software promise to overcome these problems.

15. **Non Synchronous Vibration - HCF**. The failure of an aircraft's gas turbine engine can be catastrophic. Similarly, millions of aviation industry maintenance man-hours are spent each year inspecting for the precursors to HCF damage. HCF is caused by resonance, and whilst its effects in a gas turbine can be reduced by avoiding/eliminating resonance at the design stage, changes in usage or configuration can unknowingly introduce HCF. HCF differs from Low Cycle Fatigue (LCF) in that the fatigue mechanism from varying loads of smaller amplitude but much higher frequency. This will cause rapid propagation of a crack and lead to failure in a short time. The combinations of parameters which generate HCF are much more difficult to define and predict, than the well characterized conditions which are associated with LCF. An accurate and effective means of monitoring HCF damage and diagnosing it would be essential for COEHM system.

16. **Real-Time Vibration Monitoring & Improved Vibration Analysis**. The need to measure true individual blade vibration is essential to any active vibration control system or to accurately deduce where a component is on its life to failure curve. The current technology of using accelerometers is adequate for determining out of balances or identifying a pump malfunction, but they have application and environmental limitations. Therefore new approaches are required to the measurement, in real time, of vibrational forces being experienced inside an engine. The technologies that could be used are almost limitless, but some of the current thinking is towards:

a. **Acoustic**. Required only to pick up the acoustic changes in a passing blade, but does require an expert interpretation of the resolved frequencies. The sensor is passive in that it only receives and has no emit requirement. The rotational speed as well as pressure can also be easily monitored.

b. **Blade Tip Deflection Sensors**. This system uses time measurement to determine the dynamic tip deflection. The optical probes are located over the blades being monitored and laser light is used to detect changes in the position of a blade, and as such can be directly related to vibration2. The reflected light process is more complex than an acoustic sensor but can provide rotational speed as well as thermal data when used in conjunction with thermographic phosphors.

c. **Eddy Current**. With a eddy current probe mounted on the shaft then any changes in an electro-field can be resolved directly into a vibration. The system can also deduce rotational speed and torque. The inherent property of a rotating mass is that it vibrational signature changes dramatically if it has a defect, and as such this approach could also detect blade or disc cracks.

d. **Oil Monitoring**. The use of in line real time oil monitoring3 will identify the mass and density of any bearing material in the oil system. As bearing break-ups follow a characteristic burn out curve the comparison of vibrational data and bearing debris data will help identify more accurately incipient bearing failures.

17. **Real-Time Crack Detection**. The ability to accurately design and so predict a defect free component is driven by the need to control life cycle costs within technology constraints. The greater the need to produce a defect free component then the greater are the potentials to gain additional cost or performance benefits (design and manufacturing cost reductions, weight reductions, life extension and improved damage tolerence). However there will never be a point of zero failure and so we must consider the need for a real-time crack detection system. The current technologies would lend to the development of a system to detect cracks using eddy currents or X-Ray Tomography4.

IMPROVED LIFE ALGORITMS

18. The effectiveness of monitored data depends on how it is interpreted. The used of life algorithms are well understood to equate a total life as well as deduce a life used. To date the accuracy of these algorithms have been adequate, but a more precise approach is now required. The tracking of engine usage has progressed from manually recorded engine operating time to today's standard of total accumulated cycles based on monitoring of speed gates. Even today's approach, however, is a rough approximation of actual life consumption during normal engine operation. These rough approximations result in considerable uncertainty in setting inspection intervals, and can result in inspections occurring too late, impacting safety or too early, impacting availability. The development of advance life algorithms rely on design structural analysis equations and on-board measurements to improve accuracy. The use of Probabilistic as a design and life tool was defined at para 10 and reflects the current thinking on more accurate life predictions.

CONCLUSION

18. The USAF has set itself goals for capability, performance and reliability standards that it must achieve if it is to maintain air superiority. The advent of novel design methodologies and materials has put the spot light on engine diagnostics and prognostics as an essential element to achieve those goals. The development and implementation of the COEHM Methodology will help meet the set Autonomics goals and the needs of the third millennium. The development of a totally sensed engine (real or virtual) that provides exact and accurate data will help a COEHM system perform the AI function that is required to derive fast and accurate answers; this will enable the maintainers to quickly regenerate an aircraft for it next mission. The COEHM is more than just an approach but an asserted effort to produce a range of compatible EM systems for 2001 and beyond.

REFERENCES

1. Roemar, M. J. and Atkinson, B. "Real-Time Engine Health Monitoring and Diagnostics for Gas Turbine Engines." SAE Aerospace Atlantic Conference, May 22-23 1996, Dayton, Ohio.

2. Stange, A. W. "Non-Intrusive Sensing Techniques for Advanced Turbine Engine Structures." SME Gas Turbine and Aeroengine Congress and Exposition, June 11-14 1990, Brussels, Belgium.

3. Muir, D. and Howe, B. "In-Line Oil Debris Monitor". SAE Aerospace Engineering Oct 96, p9 to 12.

4. Kirchner, T. Burstein, P. and Youngberg, J. "Spin Synchronous X-Ray Sinography for Nondestructive Imaging of Turbine Engines Under Load." U.S. DOT/FAA Final Report # DOT/FAA/94/01 June 94.